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The thermometric movements of tree branches at freezing temperatures*

C. C. TROWBRIDGE

(WITH NINETEEN TEXT FIGURES)

During the winter of 1910, the writer of the present paper noticed that the branches of several linden trees on the grounds of Columbia University in the City of New York changed their position when a fall of temperature below freezing occurred.

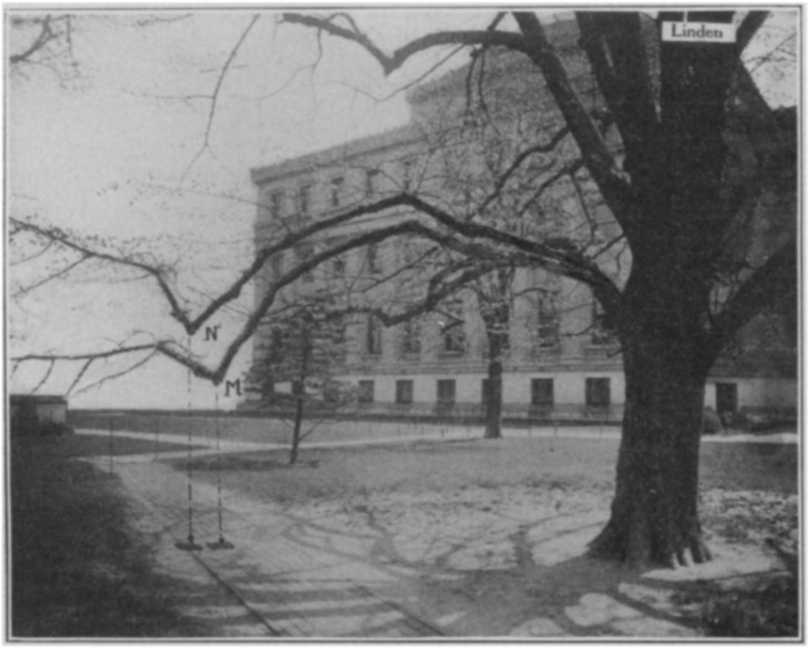

FIG. 1. Photograph showing the extent of the change of the position ot a branch of a European linden tree (*Tilia europaea*) between normal and about twenty-two degrees below freezing, Fahrenheit. The lower branch (*M*) has been artificially inserted in the photograph to show extent of movement. Lower branch, at elbow, *M*, 5.33 ft. elevation, temp. + 10° F., February 10, 1912. Upper branch, at elbow, *N*, 6.82 ft. elevation, temp. + 35.6° F., February 28, 1912. This branch is designated as "Branch *A*, Tree No. 1," in the accompanying curves.

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[1] Contributions of the Phoenix Physical Laboratory, No. 34.

The matter was again strikingly called to mind during an exceedingly cold period in the early part of February, 1912. As the phenomenon seemed not to be generally known among botanists, a series of measurements was made to ascertain the extent of the movements, and, if possible, to learn something of their origin.

During the course of the work, two or three papers on the subject came to light, two of which anticipated the observations of the writer with respect to the general phenomena of the thermometric movements of branches of large trees. Since, however, the field of the investigation has been extended in several respects, and because the matter is so little understood, the observations made are published in full in the present paper.

The general facts relating to thermometric movements of branches of large trees as based on the writer's observations are as follows: It appears in the case of certain species, particularly the European linden (*Tilia europaea*), that when the temperature of the air reaches the freezing point of water, 32° F. (0° C.), the branches of the tree, large and small, begin to bend and continue this movement with further reduction of temperature. At the lowest temperature measured, about 0° F. (– 17.5° C.), the ends of the large branches of a particular linden under observation showed depressions as great as from three to five feet below their position at 32° F. The movements of the branches were found in general to correspond closely to the changes in temperature of the surrounding air, as will be shown. The observations made consisted of daily and hourly records of the height of branches of several species of trees with corresponding meteorological data. The work has been supplemented by photographs. The relation of the air temperature and the relative humidity to the observed changes in the branches will be presented in the form of curves.

The subject is an important as well as an interesting one, since frost cracks of the linden have been found by the writer to accompany in no accidental manner the thermometric movements of the branches. Frost cracks have much to do with the injury to various trees by insects and by decay, a matter well known, and at present a subject of investigation by the Bureau of Plant Industry of the Department of Agriculture of the United States.

HISTORICAL

A brief summary of the contents of papers relating to the subject of this paper is given below.

It is a noteworthy fact that comparatively little is to be found in the literature on the thermometric movement of branches of trees. Moreover, references in recent botanical papers to the few contributions on the subject are rare indeed; it is for this reason that the phenomenon is not well known among botanists. The writer was at first unable to find any published account of the gross thermometric movements to be described, but after the observations had been partly completed, his attention was called by Dr. J. T. Grossenbacher, of the Bureau of Plant Industry, Washington, D. C., to two papers on the subject, one by Robert Caspary, and the other by N. Geleznow, which were published in 1866 and 1872 respectively. Dr. Grossenbacher, having observed an abstract of the writer's observations,* published an article chiefly devoted to a discussion of these two early researches.† To quote from a footnote in his paper: "This review of the literature of branch movements and observations grew out of a study of crown-rot of fruit trees and is published separately because it is only indirectly related to the main theme." Owing to the publication of a review of these papers, they are referred to more briefly in the present paper than otherwise would have been the case.

Mr. John Rogers, at Kent, England, was apparently the first to observe the movement of large branches of trees in cold weather. His first observations were made as early as 1838, and a short note on the observations was published a few years later.‡

In 1865, Professor Caspary, of Königsberg, made a series of measurements of the phenomenon observed by Rogers, on a number of species of trees in the Königsberg botanical gardens. The observations were published under the title, "Über die veränderungen der Richtung der Äste holziger Gewächse bewirkt durch niedrige Wärmegrade."§ Caspary found three types of

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* Branch movements of certain trees in freezing temperatures. Torreya 13: 86–87. 1913.

† Branch movements induced by changes of temperature. Science II. 38: 201–205. 1913.

‡ Trans. Hort. Soc. London II. 2: 230. 1842.

§ Internat. Hort. Exhib. Bot. Congress 98–117. 1866.

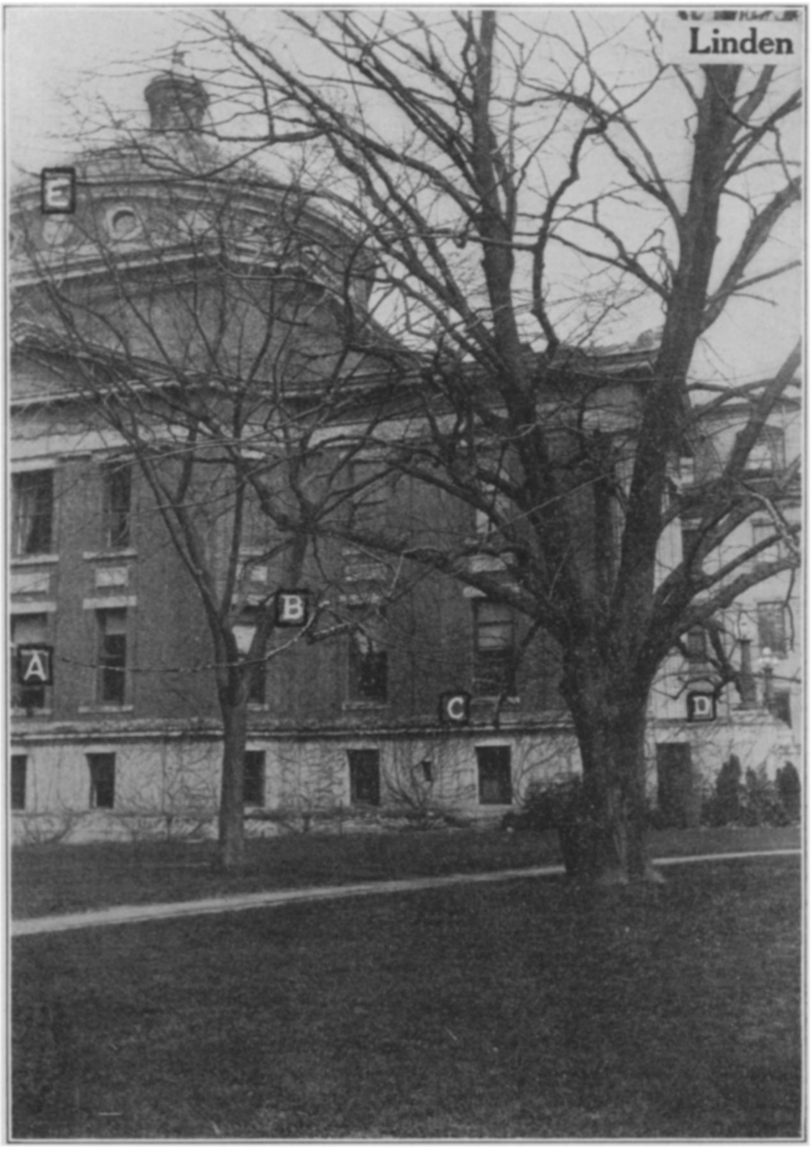

FIG. 2. Photograph of European linden tree No. 1, when the air temperature was + 50° F. Branches at normal level. Note positions of branches at *A*, *B*, *C*, *D* and *E*.

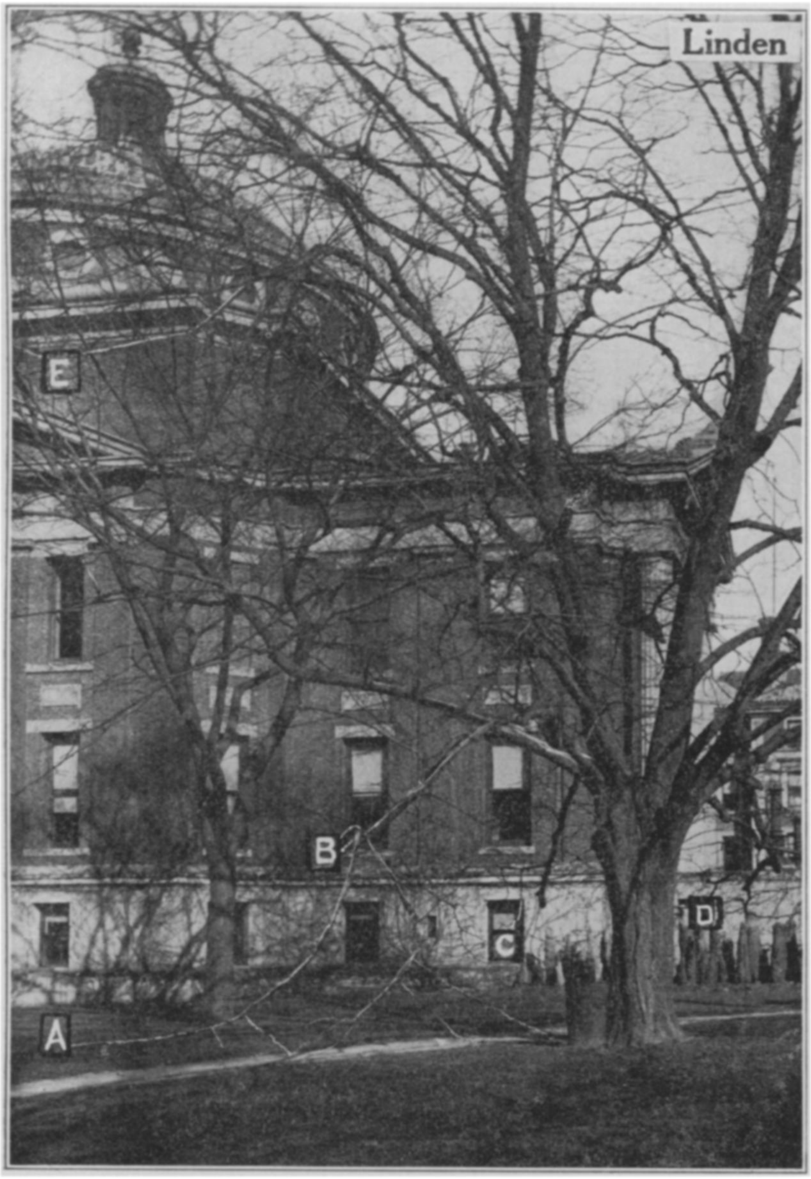

FIG. 3. Photograph of European linden tree No. 1 at + 14° F. (18° below freezing) showing marked depression of branches. See position of branches at *A*, *B*, *C*. *D* and *E*.

movements accompanying a fall of temperature. In one class, (*a*), the branches became depressed; in the second, (*b*), they rose at first, then with continued fall of temperature became depressed; and (*c*) they became elevated without being depressed. The measurements were carefully made on ten species of trees. No definite conclusion, however, as to the cause of the movements was arrived at by Professor Caspary, although he suggested the theory that the movements were caused by a differential expansion between the upper and lower sides of the branches.

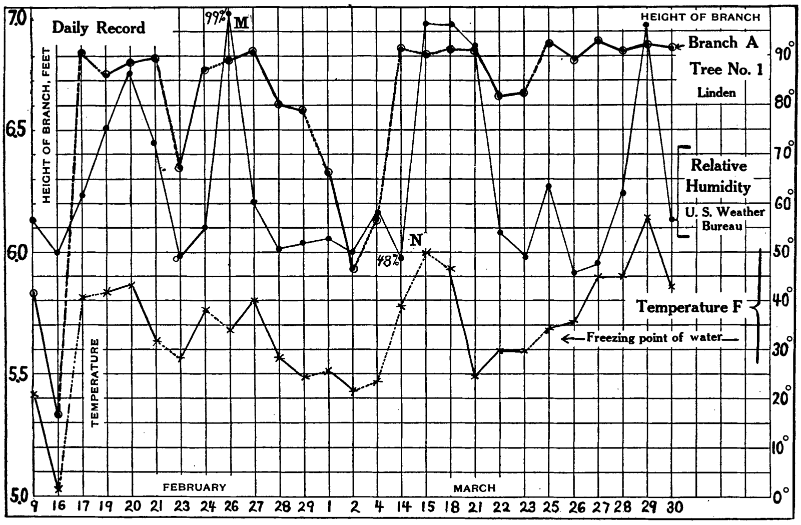

FIG. 4. Daily record of Branch *A*, Tree No. 1 (European linden) during *February* and *March*, 1912. Broken lines indicate where the daily record was not continuous. The branch movements are seen to follow closely the air temperature changes when *below freezing*. The amount of atmospheric moisture present, as shown by the relative humidity record (fine line curve), apparently has little effect on the position of the branch.

Later the following paper appeared: "Recherches sur la quantité et la répartition de l'eau dans la tige des plantes ligneuses," by N. Geleznow.* This contribution deals chiefly with the amount of moisture in the various parts of branches and tree trunks. Observations on the change in the position of branches with change of temperature were also made. Geleznow stated that he had first noted the phenomenon in 1854–5, and experiments made by him in 1864 and 1865 showed that the excentric position of the medullary canal in some species had a marked influence on the phenomenon, but there were some anomalies which could not be explained. Experiments made in 1865–1867 showed a slight relation of the water content of the branches to the thermometric movement of the branches, but the connection was not at all definite. The work was undertaken largely to find an explanation of Caspary's work at Königsberg, already referred to.

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* Bull. Acad. Imp. Sci. St. Petersburg **9**: 667–685. 1873–1877.

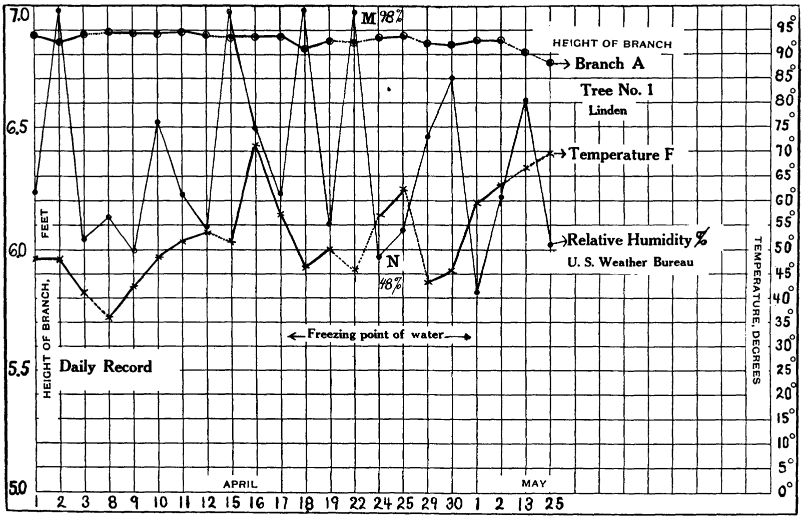

FIG. 5. Daily record of Branch '*A*, Tree No. 1 (European linden) during *April* and *May*, 1912. Little or no movement appears to accompany the large changes of both the air temperatures (all above 32° F.) and the relative humidity. The depression in the branch during *May* is due to the weight of the leaves.

A letter in Nature, entitled, " Position of boughs in summer and winter," by Agnes Fry,* records the height of branches of both a mulberry and a walnut tree in summer and in winter. The measurements show the reduced height in summer due to the weight of the leaves. The changes amounted to one foot or slightly more. This note is not pertinent to the subject under discussion since the movements observed were not thermometric.

In 1898, there appeared a paper of similar character to the last, entitled, " Preliminary observations of the seasonal variation of a branch of a horse chestnut tree," by Miller Christy.†

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* Nature 54: 198. 1896.

† Jour. Linn. Soc. Bot. 33: 501. 1898.

The measurement reported consisted in the change in height of a branch of this species due to the growth and to the fall of the leaves. The height decreased in April and May, coincident with the growth of the leaves. Then followed a period of rest, but in August and September there was a further depression. In October, the branch rose with the fall of the leaves, the maximum variation being about one foot. "During the winter months, very little change in the elevation of the branch was observable, as shown by the observations, etc." No temperature changes were recorded. It is seen that this paper does not relate to the problem under discussion.

" An undescribed thermometric movement of the branches of shrubs and trees," by W. F. Ganong,* is in some respects closely connected with the work of Caspary and Geleznow and with the observations made by the writer of the present paper.

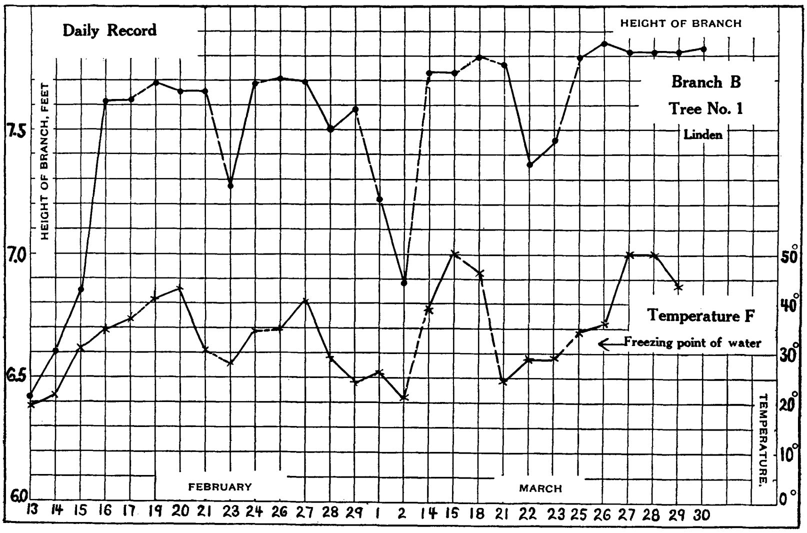

FIG. 6. Daily record of the movements of Branch *B*, Tree No. 1 (European linden) during *February* and *March*, 1912. The movements correspond closely with those of Branch *A*, in FIG. 4, although some of the observations were on different days.

Ganong's observations related mostly to the movements of twigs of shrubs and very small trees, and scarcely exceeded 12 cm. There is no mention, moreover, of the important fact (as in the case of large trees) that the movement begins when the temperature of the air reaches the freezing point of water.

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* Ann. Bot. **18**: 631–644. *f. 52–57.* 1904.

Two movements are described, a gradual seasonal displacement, and a secondary, depending indirectly on thermometric changes. Whether the latter is similar to the one to be described is difficult to ascertain. Ganong has performed some important experiments, and concludes that the secondary movements are correlated with changes in temperature *but that they are not directly caused by temperature.*

Miss Jean Broadhurst* is the author of a note entitled, "The weeping willow in winter," describing the observation that the slender unbranched twigs of this tree (twigs one to two feet long), which in November hang vertically, become curled up during the early winter so that the ends of the twigs are above their origin. The phenomenon appears to be a seasonal one rather than one depending on temporary temperature conditions. A further note on the subject entitled, "Winter changes in the weeping willow," was published later.† It is possible that the

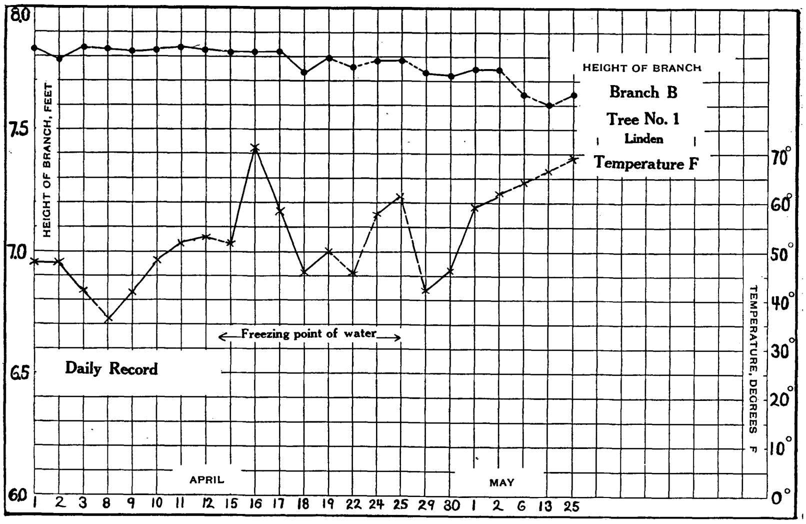

FIG. 7. Daily record of Branch *B*, Tree No. 1 (European linden) in *April* and *May*, in 1912, showing the same effect exhibited by Branch *A*, in FIG. 5, including the drooping in May due to the weight of the leaves.

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* Torreya **10**: 38, 39. 1910.

† Torreya **14**: 31, 32. 1914.

movements here described may be similar to those made on small shrubs by Ganong.

Observations by the writer in 1912 and 1913

The measurements conducted during the early part of 1912, described below, were not made under the most favorable circumstances, because it was near the end of the winter when the striking effects were noted and the measurements begun; also, there were few unusually cold periods during the winter of 1912–13. Enough observations, however, were taken to exhibit some interesting facts. Most of the observations in February, March, April and May, were made with Mr. E. Sweitzer, a special student in Columbia University. The observations during the winters of 1913–14 and 1914–15 were more extended and were made by the writer alone.

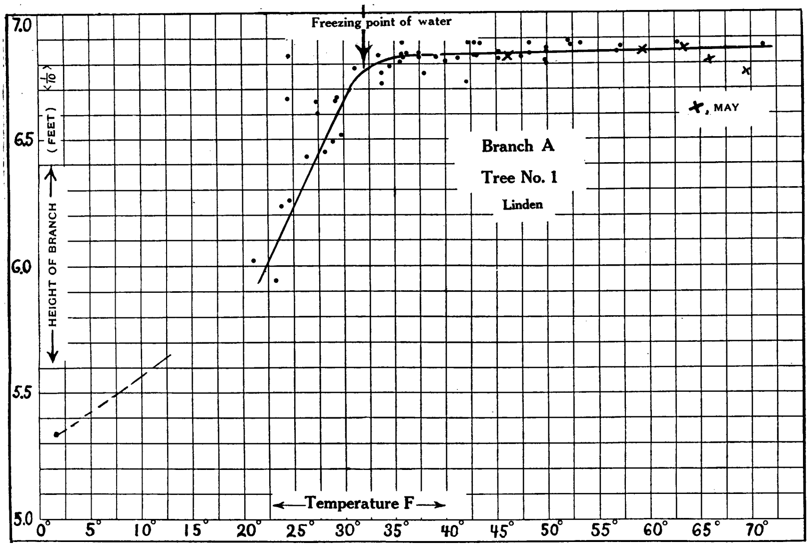

Fig. 8. Curve showing the relation of temperature change to height of branch in the case of Branch *A*, Tree No. 1 (European linden). The curve shows a point of inflection at the freezing point of water. The variation among the observations is due to temperature lag or to strain in the branch as determined by hourly records of the thermometric movements.

A study of movements of the branches of trees under freezing temperature was taken up solely on the physical side of the subject, the problem being to find the atmospheric conditions under which the movements took place, and to determine the extent of the effect produced. To illustrate the interesting phenomenon under discussion, photographs (FIGS. 1–3) have been taken.

In FIG. 1, the extent of movements can be seen at a glance. The photograph has been artificially arranged with the addition of a duplicate photograph of a branch, fitted in according to scale, and is given here solely to show the magnitude of the effect. The upper branch shows the position as it was at 32° F. or above; and the lower one, the same branch as it was at approximately 10° F. This very large movement shown indicates some interesting processes going on within the living portion of the branch.

METHOD OF MEASUREMENT AND SPECIES OF TREES STUDIED

The apparatus used consisted of a specially constructed measuring rod, a steel tape, and thermometers. The linear measurements are given in feet and hundredths of feet. The temperatures are given in Fahrenheit as being more convenient, although many sets were taken in Centigrade. The Fahrenheit scale was used to compare temperatures with temperatures taken from a record of the United States Weather Bureau, which are expressed in Fahrenheit. Also, the temperature curve continually crossed the freezing point of water; hence the use of the Fahrenheit scale avoided the employment of the + and − sign. The heights of four branches from the ground were measured, three species of trees being selected, and also the distance from the point on the branch measured, as indicated by a plumb line, to the trunk of the tree in a horizontal line. The latter measurements are not given in this paper, since they correspond in general to the vertical measurements.

Two similar curved branches of a European linden tree designated as Tree No. 1, were measured; also, a branch of a *Paulownia tomentosa*, designated as Tree No. 2, similar in shape to the branches of Tree No. 1, and a horizontal branch of an oriental plane-tree or sycamore (*Platanus orientalis*) recorded as Tree No. 3.

It was to be regretted that branches of the linden of various shapes were not measured, but the observations that were made absorbed a good deal of time, and the desirability of an extension of the records to branches of different forms was not foreseen.

Temperature and relative humidity observations taken from the United States Weather Bureau have been used in a few cases. The Draper Observatory in Central Park, where these observations were made, is not more than three miles distant from the Columbia University grounds, and since it was shown by the thermometer records at the two places that the temperatures were usually within a degree or so of each other they agree sufficiently in the present case. No relative humidity observations were made, but the Draper Observatory record of the moisture was sufficiently close for the use to which it was put, since large changes in relative humidity appeared to have little or no effect on the position of the branches.

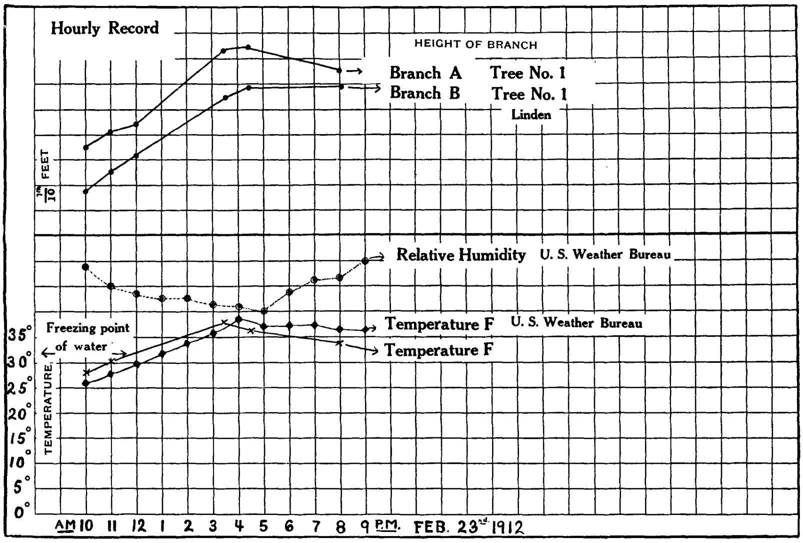

FIG. 9. Hourly record of Branches *A* and *B*, Tree No. 1 (European linden), showing rise of temperature through the freezing point and subsequent fall. Here the branches appear to respond quickly to the changes in temperature and there also appears to be a slight thermometric movement *above freezing*.

DAILY RECORDS AND EXPLANATION OF CURVES SHOWN IN FIGS. 4, 5, 6, 7 AND 8

The daily record of Branch *A*, Tree No. 1 (linden), is given in FIGS. 4 and 5, for February, March, April and May. The facts shown by these curves are as follows:

The temperature when above 32° has little effect on the position of the branch, but whenever the temperature of the air passes below the freezing point of water, an immediate bending of the branches of the tree takes place. Throughout April and for some observations in May, very little change in the position of the branch takes place, except depression of the branch due to the weight of the leaves in May. Notwithstanding the fact that during April and May there was a large variation in temperature, no movement took place because all the temperatures were above 32° Fahrenheit. In regard to the influence of water vapor present in the atmosphere on the movement of the branches, it can be seen by the fine line curve in FIGS. 4 and 5, representing relative humidity, that there is little, if any, effect. This is specially evident at points *M* and *N* in both figures, where the humidity was high and low respectively with apparently little influence on the height of the branch. The curves in FIGS. 6 and 7 made with a different branch show effects similar to those observed in the case of Branch *A*. The curves corresponded very closely

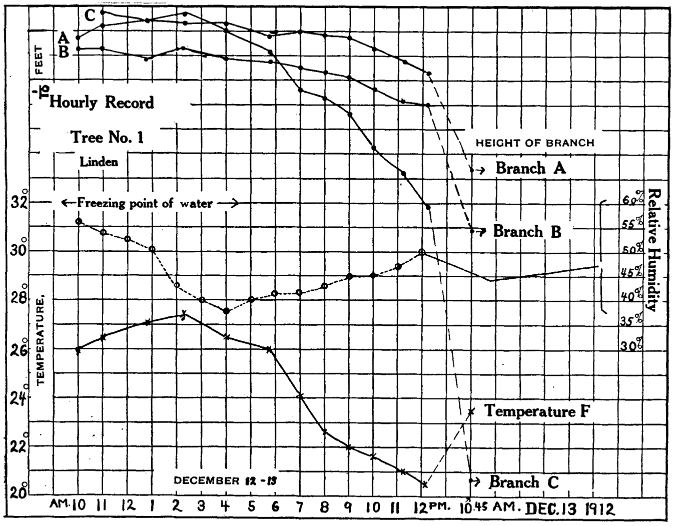

FIG. 10. Hourly record of Branches *A*, *B*, and *C*, Tree No. 1 (European linden). Temperature on a large scale. Branch *C* observations were made at the extremity of a branch. The last reading was taken at 10.45 a.m., the previous observation at 12 midnight preceding.

for Branches *A* and *B*, except that the days of observation were somewhat different. In FIG. 8, the relation of the variation in height of Branch *A* (same as FIGS. 4 and 5) to the variation of temperature is shown. It is seen at once that there is a marked point of inflection of the curve at the freezing point of water. The fact that the observation points do not fall on the curve is significant and will be presently explained. While the major effect of the temperature is below 32° F., there is evidently a minor thermometric effect just above 32°, which, however, is so small as perhaps to be due to a warping of the branch due to internal strains arising from the bending of the branch, caused by below freezing temperatures a short time before the observations at warmer temperatures were made. Thus the behavior of the branch depends somewhat on its immediately previous history.

HOURLY RECORDS AND EXPLANATION OF CURVES IN FIGS. 9, 10 AND 11

In these curves, an hourly record was kept of several of the branches of Tree No. 1 to ascertain how soon the branch responded

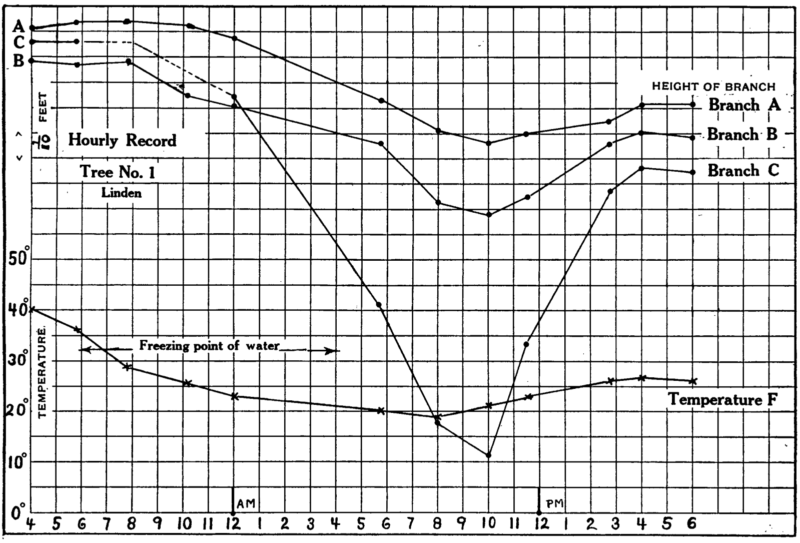

FIG. 11. Hourly record of Branches *A*, *B*, and *C*, Tree No. 1 (European linden), showing the effect of a fall in temperature below freezing and the subsequent rise. Observations of Branch *C* were at the end of the branch. These curves demonstrated the lag in the movements of the branches with fairly rapid changes of temperature and explain the variations among the observations shown in the curve in FIG. 1.

to the changes in the temperature of the air. While observations were not taken every hour, they were frequent enough to obtain the results required. It is seen in FIG. 9, which gives observation where the temperature rises to a maximum just *above the freezing point of water*, that both branches begin to fall with the temperature within a quarter of an hour after the high point of the temperature has been reached and before the temperature passes through the freezing point. This seems to show that there is a very small thermometric effect just above 32° F. The same fact is indicated in other observations. In FIG. 10, three branches were measured and the resulting curves show the effect on the branches when the temperature of the air *rises to a maximum, below the freezing point of water*, and then falls again. C observations in this set were taken at the extremity of the branch and hence show the largest movement.

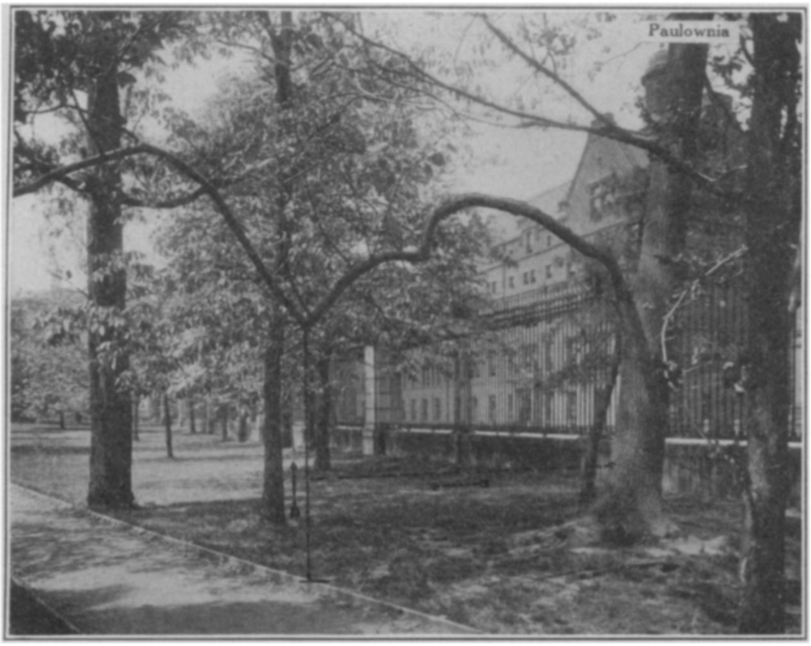

FIG. 12. Photograph of Branch *A*, Tree No. 2 (*Paulowina tomentosa*). This branch showed little or no thermometric changes. The branch was selected because of its similarity in shape to Branches *A* and *B*, Tree No. 1.

In FIG. 11 the readings of three branches were taken under conditions where the temperature had fallen to about 20° F. and then rose. Here it is clearly shown that there is a lag amounting in time to about two hours before the branches begin to move upward, although a change in the *rate of the depression* is observed to take place as soon as the temperature of the air begins to rise. The effect on the branch of a change of temperature is therefore almost immediate with a lag depending on various conditions. It is probable that the size of the branch is the ruling factor, the very small branches responding almost at once to change in temperature.

EXPLANATION OF CURVES SHOWN IN FIGS. 13 AND 15

In FIG. 13 the daily record from February to May of a *Paulownia* (*P. tomentosa*), Tree No. 2, is shown. The branch measured has the same shape as that of the linden branch shown in FIG. 1. Here it is seen that there is little or no thermometric effect due to the changes of temperature of the air, although the

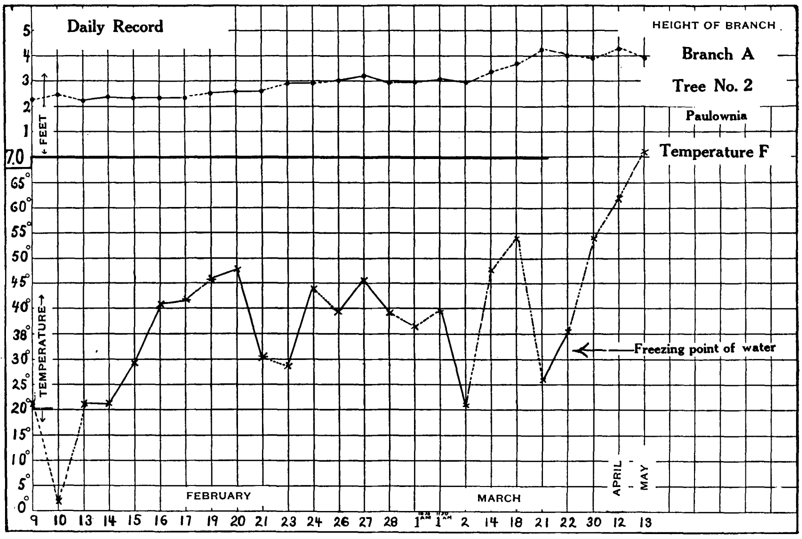

FIG. 13. Daily record of Branch *A*, Tree No. 2 (*Paulownia tomentosa*). Record for *February, March, April* and *May*. No appreciable change is shown which accompanies below freezing temperatures,—but a gradual rise from February to May is evident and a particular response to warm days during that period is apparent.

temperature repeatedly passed through the freezing point of water. There is, however, a continual rise of the branch from early in February till May. This elevation is evidently a response to heat and light of the sun, and being a seasonal change, is an entirely different effect from that observed in the linden.

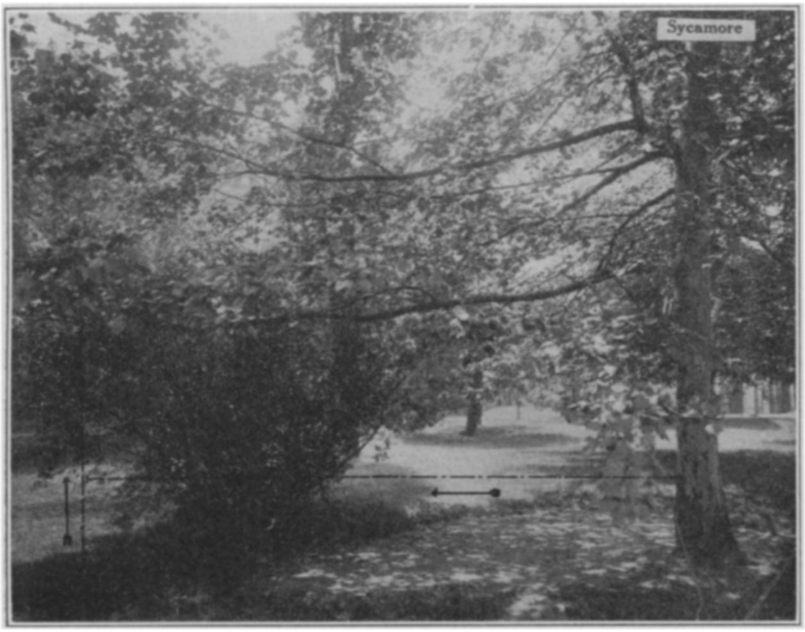

Fig. 14. Photographs of Branch *A*, Tree No. 3, sycamore (*Platanus orientalis*). Measurements shown in Fig. 15. This branch differed from others measured in being straight and nearly horizontal.

In Fig. 15 an intermittent record of the height of a straight branch of a sycamore tree, *Platanus orientalis*, Tree No. 3, from February to well along in April, is given. Here also no thermometric movement is observed, the gradual rise of the branch recorded being a seasonal change. These observations merely show that in certain trees there is no thermometric movement of the branches.

THE ELASTIC CONSTANT OF BRANCHES ABOVE AND BELOW FREEZING

In Fig. 16 is shown a plot of an experiment which consisted in weighting the branches of both Tree No. 1, the linden, and Tree

No. 2, the *Paulownia*. Sixty-five pounds were added to the branch, five pounds at a time. This experiment was made both at a temperature above freezing, and also at a temperature well below freezing. It is seen that the constant of elasticity has changed in both cases, and the amount of depression per pound has decreased for the branches of both trees at the lower temperature. It would therefore appear as if the change in the modulus of elasticity of the two branches, due to changes in the temperature, had little or nothing to do with the direct temperature effect produced in the case of Tree No. 1, the linden, which showed large thermometric movements.

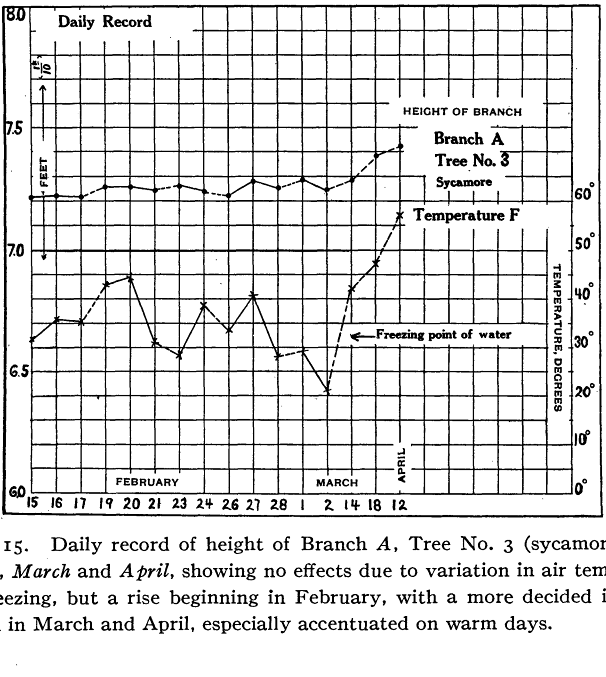

FIG. 15. Daily record of height of Branch *A*, Tree No. 3 (sycamore), during *February, March* and *April*, showing no effects due to variation in air temperatures, below freezing, but a rise beginning in February, with a more decided increase in elevation in March and April, especially accentuated on warm days.

From theory it is to be expected that if there is a change in the modulus of elasticity due to temperature, and if a stiffening occurs at low temperature, the branch would not be as much depressed. Such an effect is opposite to the large thermometric movement actually observed. In the case of the weighted cold branches a loss in recovery is noted, which is probably temporary, but explains certain inconsistencies observed on other observations.

The following experiment was tried. A branch, curved in form, was cut from the linden and at once artificially cooled to 0° F., in a salt-ice pack, but showed no change of curvature between 0° F. and 40° F. The experiment, however, was not conclusive, since the branch was not longer than about three feet. It was ascertained definitely, however, that certain branches which were curved upward on the linden became more curved when subjected to low temperature. This fact was found by attaching strings to the ends of branches which were curved

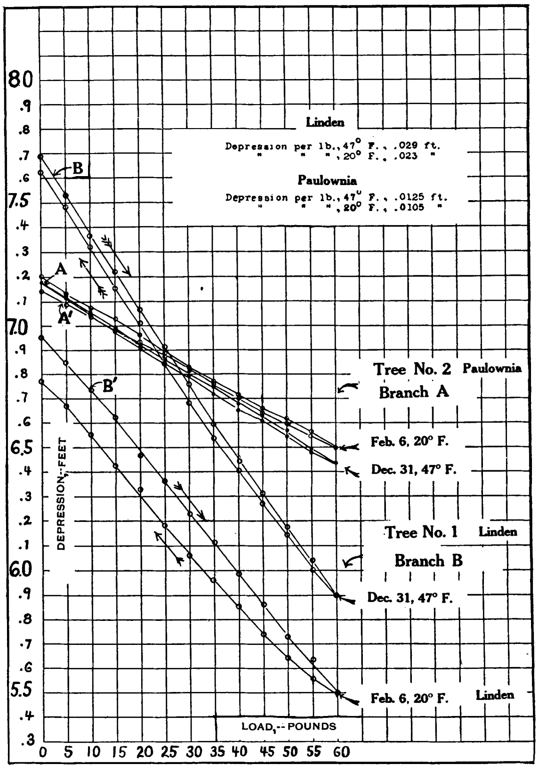

FIG. 16. Effect of loading Branch *B*, Tree No. 1 (European linden), and Branch *A*, Tree No. 2 (*Paulownia tomentosa*), at two differenttemperatures. The modulus of elasticity constant is less in both cases at temperatures below freezing, which is to be expected. A change of the constant, therefore, does not account for any part of the depression of the branches *A*, *B* and *C*, Tree No. 1 (linden), with low temperature since the effect of the change of the modulus is opposite to the thermometric movement observed.

concave upward, and observing the change of the tension on the reduction of temperature. These cords which were taut at 32° F. (or 0° C.), sagged at 15° F., showing an upward movement of branches which were concave upward. This is in agreement with observations made by Geleznow, who cut off branches, inverted them, and observed that their movement was opposite to those in the normal position.

RELATION OF FROST CRACKS TO THE THERMOMETRIC MOVEMENT

It was noticed both during the winters of 1911–2 and 1912–3 that a linden showed a decided so-called frost crack or longitudinal cleft which was wide open during cold snaps, and in one case, the crack was extended for fifteen feet along the trunk. The width of this crack varied with the temperature and closed up completely as soon as the temperature rose to 32° F. This was particularly noticeable during the coldest period of about February 10, 1912. Frost cracks in the linden are evidently due to the same origin as, or connected with, the thermometric movement of the branches, and therefore their study is intimately associated with the main theme of this paper.

The fact that frost cracks open in cold, and close in warm weather is well known.* In this connection an interesting and reliable observation reported to the writer illustrating the well-known noises caused by frost cracks is as follows. In very cold weather some lindens in a certain grove produced such loud and sharp noises that they were thought to be pistol shots, but were found to be the sudden formation of cracks in the lindens which were observed at the time.

In FIG. 17 a frost crack in a linden is shown, which was about three-quarters of an inch broad. Measurements of this crack with curves of the tree temperatures are given in FIGS. 18 and 19.

The facts shown by these curves indicate that the frost crack is not caused by a difference of temperature at successive depths of the tree trunk, but is due rather to a thermometric effect of some sort, not necessarily ordinary thermal expansion, acting on the cells of the tree, and probably those just below the bark.

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* See J. G. Grossenbacher, Science II. **38**: 204. 1913.

In FIG. 18 the frost crack is shown closing rapidly when the "Bark" (one inch deep) and the "Medium" (three inches deep) rise abruptly, while the "Deep" thermometer (five inches deep) remained nearly constant. In FIG. 19 the Deep thermometer is still below 19° F. while the frost crack is nearly closed. Moreover, in both sets of observations, the frost crack appears to close with the rise of temperature of the surface layers of the trunk.

THE ORIGIN OF THE THERMOMETRIC MOVEMENT

While there may not yet be sufficient data on which to formulate a theory for the actual mechanism of the thermometric bending of the branches, there are some salient facts which indicate the origin of the phenomenon. It has been shown, at least so far as the linden is concerned, that the movement begins when the air temperature is at the freezing point of water. The internal temperature of the small branches could not be far from that degree of cold.

In the curves published by Caspary* on the European linden showing the branch movements with temperature, there is correspondence between the temperature and branch positions, which indicates that the depressions of the branches began at the freezing point of water, but there is no mention of this in his text. Owing to the fact that a number of trees were studied, which showed various behavior with change of temperature, the matter might well have been overlooked. This opinion seems to be substantiated by the following quotation from Caspary's paper:

> "Der Grad der Kälte, bei welcher ein Sinken eintritt, kann wegen Mangel stündlichen Beobachtungen und Beobachtungen der Kälte des Holzes selbst im Innern nicht sicher angegeben werden."

Besides the linden, measurements of trees of various other species by Caspary show that the movement begins at approximately 32° F. By making hourly observation, not made hitherto, the writer has brought out some important facts; namely, that below freezing the branches respond to the changes in temperature almost immediately. Thus, as shown by the curves in FIG. 11, when the temperature falls to 20° F., and then rises, the branches at once slow up in their downward movement, and shortly after-

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* Loc. cit.

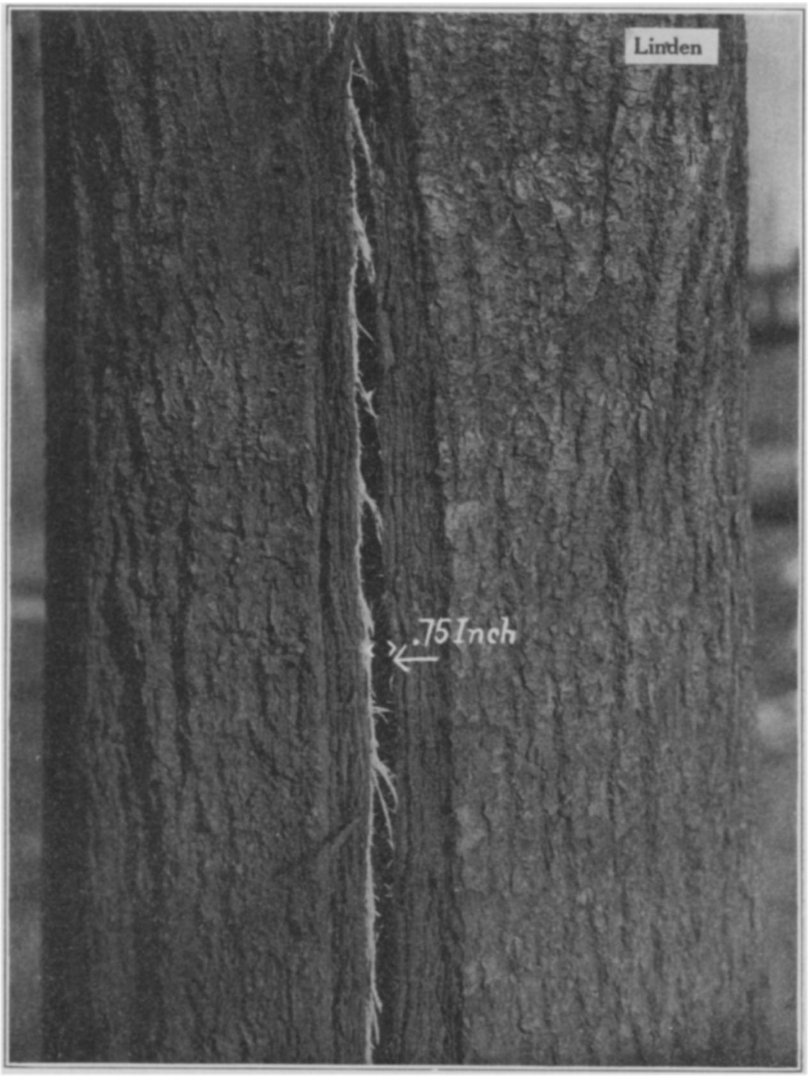

FIG. 17. Frost crack in European linden which opened and shut with changes of temperature and corresponded with movements of the branches. The measurements shown in FIGS. 18 and 19 were made on this tree.

wards move upwards. If the water in the branches was freezing as pure water, then the branches would continue to descend while the temperature remained below freezing, since ice would continue to form at any temperature below freezing. On the other hand, sap from the standpoint of physics is a solution, composed of salts of metals and of dissolved organic substances, and, as such, must freeze fractionally as the temperature is reduced. The sap thus becomes more concentrated as the freezing process continues. On a rise of temperature a fractional melting occurs.

In general, in the case of a solution composed of some salt, a point is reached where the solution will freeze at a definite temperature (in a manner similar to pure water); namely, when the solution reaches a certain degree of concentration. The indications are thus that it is the sap content of the branch rather than the water content which plays the important rôle in the thermometric movements of branches. Geleznow studied the water content of branches with little success in so far as determining the cause of the thermometric movement, and in the light of the explanation given above, negative results should be expected from a study of the water content. The mechanism bringing about the branch movements may well be a process in the living cells where enormous tension is produced in some way from the gradual separation of the ice crystals from the sap, the latter concentrating as the fractional freezing process advances. If this partial explanation is the true one, it should be expected that at some low degree of cold, certain trees would cease to show a thermometric movement of the branches, the sap having reached the so-called cryohydrate concentration where the solution would become solidified. Since the sap is a complex solution, the temperature of complete solidification would probably not be a definite one.

The question of the freezing of the tissues of trees appears not to be a proven question; yet there seems to be evidence that at least a partial freezing of trees at temperatures not far below freezing occurs.

In a paper entitled, "The Maple Sap Flow,"* experiments on

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*C. H. Jones, A. W. Edson and W. J. Morse, Vermont Agric. Exp. Sta., Bull. 103: 41–184. *pl. 1–17* + *f. 1–5.* 1903.

tree temperatures are described and the following statement made: "Casual observations made by one of the writers in mid-winter, showed maples frozen for a depth of an inch and a half in one case, and an inch in another, while both white and yellow birches were frozen through, except where the sun was beating upon them. It seems clear that some of the maple tissues are frozen in mid-winter." Also, as a summation, this view is given: "These data and observations lead to the conclusion that in the winter, the temperature of the maple tree tissues is generally below 0° C.

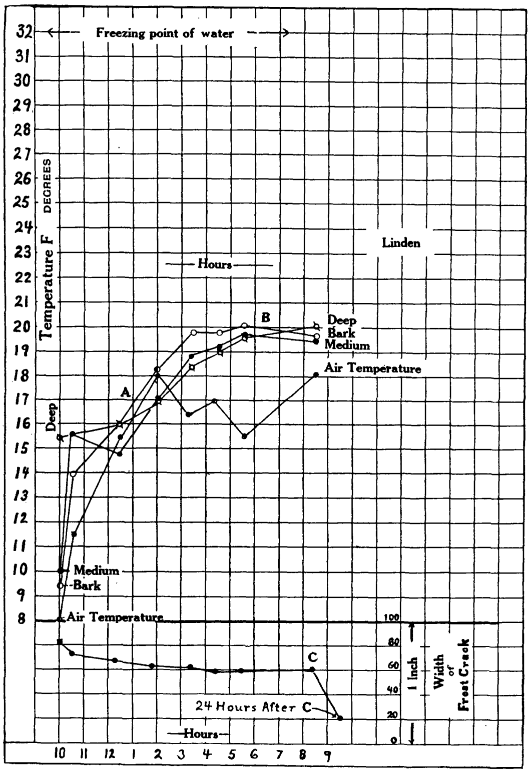

FIG. 18. Curves showing the change of width of frost crack in European linden and change of temperatures of the tree trunk and atmosphere. The bulb of the "Bark" thermometer was one inch below the surface; that of the "Medium" three inches below; that of the "Deep" five inches below. From *A* to *B* on the curves all three tree temperatures were the same. Yet the frost crack decreased in width with the general rise of temperature of the tree trunk. The mean at *A* was 15.4° F., and at *B* 19.6° F.

(32° F.), and that it may be considerably lower; that as the sugar season approaches it frequently rises above this point, and during its course is usually above, but occasionally falls below it; and that a part of the sap in the vessels of the outer rings freezes during the winter and may freeze during the sugar season."

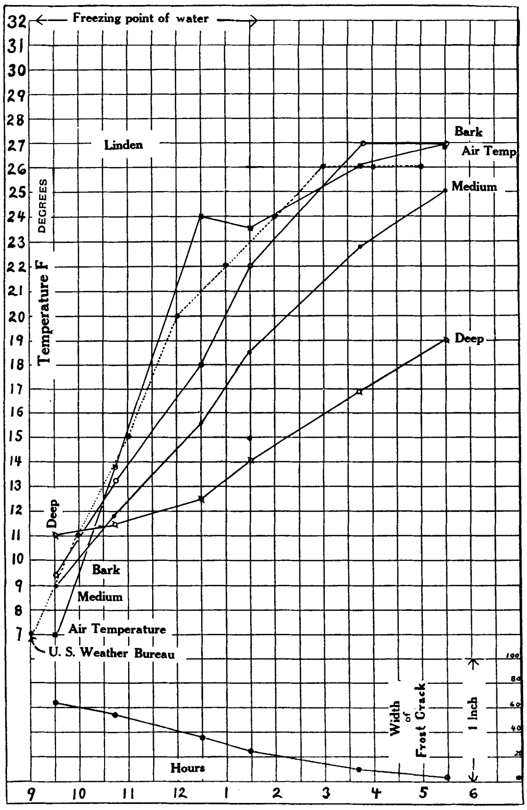

FIG. 19. Curves showing the change in width of frost crack and change of temperature of tree trunk and atmosphere. At *A* the tree trunk was at a uniform temperature to a depth of five inches. From this point on, the frost crack decreased in width consistently with the rise of temperature of the trunk of the tree. At *B*, where the thermometer readings showed the greatest difference of temperature between the successive layers of the tree trunk, the frost crack was nearly closed.

In experiments on certain plants evidence has been presented showing that freezing apparently is arrested by what appears to be a sub-cooling process; i. e., the confines of the liquid content being so small as to prevent solidification. Consequently it is possible that under certain conditions sap does not freeze (even fractionally) until at least at a very low temperature, but the evidence of the thermometric movements of branches and the thermometric opening and closing of frost cracks indicate a change which begins at 32° F. and continues below that point, which must be regarded as evidence in favor of a fractional freezing of the sap. The alternative is that there is some cellular mechanism of the living wood of the tree which begins at 32° F. and continues as the temperature falls without the fractional freezing process, but parallel to such a change of state of the sap.

A considerable number of experiments were performed in order to ascertain, if possible, the coefficient of expansion of the tree trunk just below the bark. It was found that below freezing with the reduction of temperature a very large contraction occurred in the horizontal direction, transverse to the grain; on the other hand, that there was only a very small contraction in the longitudinal direction; also, that this contraction in the transverse direction was far greater than for a corresponding range above 32° F. Owing to a number of uncertainties in the experiments, they have not been published, and have been discarded for a more accurate method, which has been devised. The results indicated correspond with some measurements of Dr. J. G. Grossenbacher,* who measured the circumferences of a number of trees and determined that for a fall of temperature the decrease in circumference per degree was greater below freezing than above that point.

The fact, mentioned above, of greater coefficient of expansion below 32° in the transverse direction also corresponds with the published observation of Caspary who found that the circumference of the bark changed more rapidly than that of the wood cylinder in certain trees.†

GENERAL CONCLUSIONS

In this investigation the mechanics of the thermometric movements of branches has not yet been determined, but the observations described have made an advance in the study of the subject. Some of the facts which have been determined are summarized below; temperatures are given in Fahrenheit for reasons previously stated.

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* Crown rot of fruit trees; field studies. New York State Agric. Exp. Sta. Tech. Bull. 23. 1912.

† R. Caspary, Neue Untersuchungen über Frostspalten. Bot. Zeit. 15: 329–35: 345–50; 361–71. 1857.

1. The measurements which have been made on the movements of large branches of the European linden (*Tilia europaea*), due to a reduction of the atmospheric temperature seem to show that below 32° F. the movements are thermometric; when the temperature of the air falls below the freezing point of water (32° F.) (or very shortly above that point) the depression of the branches begins, and continues until at least 0° F., the lowest point at which observations were made.

2. There is scarcely any movement *above 32° F.*, the level of a branch at 70° F. being approximately the same as at 32° F. The freezing action of water (the aqueous part of a solution) is therefore the origin of the process which brings about the change in shape of the branch with change of temperature below 32° F. There seems, however, to be a very slight thermometric movement just above 32° F., the data on which is uncertain.

3. By making hourly observations not made hitherto, it has been shown that there may be a lag of one or two hours in the movements of the branches behind the changes of temperature, but if the air temperature is changing, a very slight change in the rate causes an almost immediate modification in the rate of movement of the branch. The observations made thus far indicate that a constant state of temperature for a considerable time, slightly below 32° F., causes a small movement; then the branch remains stationary until the temperature changes. These facts lead to the conclusion that the freezing liquid bringing about the thermometric movements of the branches below freezing temperatures is not pure water, but a solution, namely, the sap.

4. By artificially depressing the branches by means of weights, it was found that strains in the wood cause the branch to become temporarily depressed by a small amount. These strains in the branch, and the effect of lag of position of the branch behind the temperature of the air, explain the fact that in the curves showing the relation of the position of a branch to air temperatures the points are somewhat inconsistent.

5. The degree of moisture in the atmosphere, as shown by relative humidity observations, has apparently a negligible effect on the position of the branch.

6. Modulus of elasticity experiments seem to show that there is a stiffening in the branch below freezing (32° F.); but a stiffening of the branch should produce a less mobility or less depression of the branch whatever the stress; hence the slight effect observed due to a change in the bending constant of the branch arising from a reduction of temperature, taken alone, is in the opposite direction to the gross changes of the level of the branch observed at low temperatures.

7. Observations on frost cracks of the linden have shown that the width of the longitudinal cracks follow the changes in air temperature approximately below 32° F. When the crack first opens it is not thermometric because it is greatly affected by strain conditions, and resistance in the tearing of the wood.

Thermometers placed within the tree trunk at different distances from the surface indicated that the cracks were not caused by an unequal strain between the central core of the tree and the portion of the tree near the surface, arising directly from a difference of temperature, but due rather to excessive tension conditions in the living portion of the tree directly below the surface of the trunk.

All observations made indicate in a general way that the bending of the branches is closely related to the process which produced the longitudinal frost cracks in the linden.

8. Preliminary measurements indicate that the coefficient of expansion in the living linden in the transverse directions of the wood directly below the bark is very large below freezing, while small in the longitudinal direction.

9. Experiments on a *Paulownia* (*Paulownia tomentosa*) and a sycamore tree (*Platanus orientalis*), show scarcely a trace of the thermometric movement as exhibited by the linden.

The writer begs to acknowledge the courtesies shown by Professor Harper and other members of the Department of Botany at Columbia University, who have made many helpful suggestions pertaining to the botanical side of the present investigation.

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